Machinery MESsages

Housing measurement transducers

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In a previous column (*Orbit*, June 1983), we discussed the considerations for shaft versus housing measurements on rotating machinery. We also evaluated two shaft measurement techniques, the proximity probe and the shaft rider (*Orbit*, March 1983). This column completes the series by evaluating the two most frequently used housing measurement transducers, the velocity Seismoprobe™ and the accelerometer.

This discussion is restricted to standard, commonly available vibration measurement transducers. We will consider only those transducers that have a broad range of applications on various types of rotating machinery. Specifically, we mean velocity transducers of the magnet and coil spring-mass-damper type and compression-type piezoelectric accelerometers.

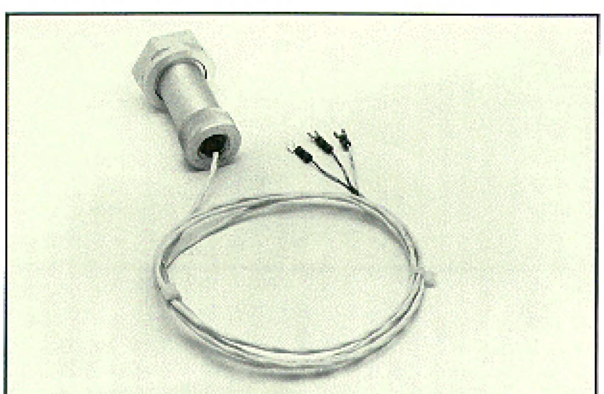
We will discuss those transducers that are typically employed for singular overall machinery evaluation in monitoring and preventive maintenance programs. Granted, there are special-purpose transducers that may be excellent for detecting and diagnosing certain specific machinery problems. But they may offer an insufficient level of overall protection for monitoring purposes unless the monitoring system is augmented by other transducer types.

Differences between velocity and acceleration measurements

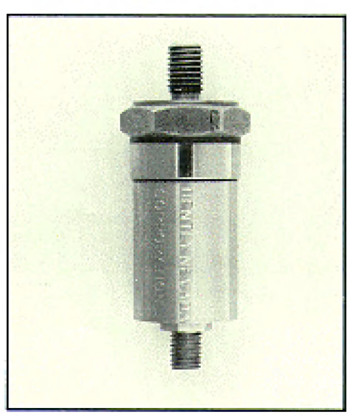
Any vibratory motion can be measured simultaneously by both a velocity and acceleration transducer, but the signal outputs of each can be significantly different. Velocity is the time rate of change of displacement. Acceleration is the time rate of change of velocity. Velocity is a direct function of vibration frequency, while acceleration is a function of frequency squared.

Since vibration measurement is an attempt to characterize the forces acting upon a machine, it would be ideal to prove that either velocity or acceleration is more representative of those forces and thus take a major step toward correct transducer selection. In fact, both sides of this question have been debated for years, with no clear winner.

Velocity Transducers: Suitable for overall monitoring of certain machine types.



Accelerometers: Mostly suitable for high frequency measurements with some overall monitoring applications in certain situations.



Proponents of velocity state that "constant force produces constant velocity." Proponents of acceleration claim that Newton was right and "force equals mass times acceleration."

Actually, vibration is the resultant interaction of harmful forces operating on the machine versus the useful (designed-in) dynamic stiffness forces in the system.

In terms of the normal rotor/bearing support system, dynamic stiffness has three components; system spring coefficient is related to displacement, damping to velocity, and mass to acceleration. Theoretically, since spring coefficient, damping, and mass contribute to the total picture, all three engineering units of vibration measurement can be valid for certain applications.

In some situations, an argument can be made for one vibration parameter (displacement, velocity, or acceleration) being superior to the others, if it can be shown that the forces acting on the system are more dependent upon one dynamic stiffness term than the others. For example, vibration below a resonance frequency is generally dependent upon the spring coefficient (machine acts like a pure spring). For these vibrations, displacement may be the most meaningful parameter.

Vibrations at and above a resonance frequency are dependent upon damping and mass, respectively. In these cases, velocity and acceleration, respectively, may provide more valuable data. From a purely theoretical viewpoint, however, most common machinery problems span the frequency spectrum from below to above resonances in the system. Consequently, displacement, velocity and acceleration can all be significant, meaningful parameters for overall machine evaluation.

Transducer Characteristics

Signal-to-noise ratio

All theory aside, and since the mechanical theory doesn't clearly favor one measurement technique over another, we must look for a more significant determinant. Transducer sensitivity and signal-to-noise ratio are important considerations in any selection process.

Since velocity and acceleration represent two different measurements, vibration amplitudes expressed in both units can

be significantly different for the same vibratory motion. A transducer's sensitivity (scale factor) determines its signal output level. This, combined with the actual vibration motion amplitude, defines the signal-to-noise ratio.

For example, a sinusoidal vibration with a frequency of 100 Hz (6000 cpm) and displacement amplitude of 1 mil (25 microns) peak-to-peak has an equivalent velocity amplitude of 0.3 in./sec. (8 mm/s) 0-to-peak and an acceleration amplitude of 0.5 Gs 0-to-peak. Considering the sensitivity of typical transducers—500 mV per in./sec. (20 mV per mm/s) 0-to-peak for velocity and 100 mV per G 0-to-peak for acceleration (also the American Petroleum Institute (API) 678 Standard)—these amplitudes would yield signal output levels of 150 mV and 50 mV 0-to-peak, respectively.

Both of these amplitudes represent good signal levels, well above the noise floor, i.e., a good signal-to-noise ratio. However, further comparisons will show that as vibration frequency decreases, the signal-to-noise ratio for an accelerometer decreases more rapidly than for a velocity transducer.

As an example, for a 1 mil peak-to-peak displacement at 50 Hz (3000 cpm), the velocity and acceleration amplitudes and transducer output levels would be 0.16 in./sec. (4 mm/s) or 80 mV 0-to-peak and 0.13 Gs or 13 mV 0-to-peak, respectively. Both signal levels are still above the noise floor, but the margin is less for the accelerometer.

Finally, for a 1 mil displacement at a low frequency of 10 Hz (600 cpm), the numbers would be 0.03 in./sec. (0.8 mm/s) or 15 mV for velocity, and 0.005 Gs or 0.5 mV for acceleration. In this case, the velocity output is still barely satisfactory, but the acceleration output is clearly not. This data is summarized in Table I.

This comparison was based on a constant displacement amplitude. Table II summarizes the data using a constant velocity amplitude, and the signal-to-noise comparison would yield the same conclusions.

Thus, using a standard accelerometer for low frequency measurements may be difficult, particularly if the accelerometer is simultaneously measuring vibrations at significantly higher frequencies. In this case, the low amplitude low frequency components may go unnoticed in the relatively higher overall signal level.

In summary, transducer selection based on signal-to-noise ratio requires first an identification of the anticipated vibration frequencies based on the potential machine problems and then an approximation of the vibration amplitudes at those frequencies. This discussion is based on sensitivities of standard Bently Nevada products. Most competitive units in the marketplace have a similar relationship. In fact, only a few standard seismic transducers from other manufacturers have higher sensitivities than Bently Nevada seismic transducers, and those are mostly velocity pickups, not accelerometers.

Frequency response

Again, with reference to Bently Nevada products, the frequency response of one the standard velocity seismoprobes is 4.5 Hz to 1 KHz, and for an accelerometer 5 Hz to 20 KHz, both at -3 dB. Thus, from this data alone, it would seem that the

TABLE I

INPUT VIBRATION		OUTPUT FROM VELOCITY PICKUP		OUTPUT FROM ACCELEROMETER	
FREQUENCY CPM	DISPLACEMENT AMPLITUDE MILS PEAK-PEAK	AMPLITUDE INCH/SECOND 0-PEAK	SIGNAL LEVEL* mV 0-PEAK	AMPLITUDE g's 0-PEAK	SIGNAL LEVEL* mV 0-PEAK
6000	1.00	0.31	155	0.51	51
3000	1.00	0.16	80	0.13	13
600	1.00	0.03	15	0.005	0.5

*Signal levels are based on transducer sensitivities of 500 mV per inch/second (20 mV per mm/s) 0-peak for velocity and 100 mV per g for acceleration.

Comparison of Velocity and Acceleration Levels

Comparison is based on a constant vibration displacement amplitude of 1.0 mils peak-to-peak. English units only are shown for simplicity. Metric conversions are: 1.0 mils = 25.4 microns; 1.0 inch/second = 25.4 mm/second.

TABLE II

INPUT VIBRATION		OUTPUT FROM VELOCITY PICKUP		OUTPUT FROM ACCELEROMETER	
FREQUENCY CPM	DISPLACEMENT AMPLITUDE MILS PEAK-PEAK	AMPLITUDE INCH/SECOND 0-PEAK	SIGNAL LEVEL* mV 0-PEAK	AMPLITUDE g's 0-PEAK	SIGNAL LEVEL* mV 0-PEAK
6000	0.64	0.20	100	0.33	33
3000	1.27	0.20	100	0.16	16
600	6.37	0.20	100	0.03	3

*Signal levels are based on transducer sensitivities of 500 mV per inch/second (20 mV per mm/s) 0-peak for velocity and 100 mV per g for acceleration.

Comparison of Velocity and Acceleration Levels

Comparison is based on a constant vibration velocity amplitude of 0.2 inch/second (5.08 mm/s) zero-to-peak. English units only are shown for simplicity. Metric conversions are: 1.0 mils = 25.4 microns; 1.0 inch/second = 25.4 mm/second.

TABLE III

TRANSDUCER CHARACTERISTIC	VELOCITY	ACCELERATION
Engineering Unit as Representative of Force	(Equally Applicable for Certain Applications)	
Signal-to-Noise Ratio	Good Over Specified Range	Poor for Low Frequencies
Frequency Response	Typically 5 Hz to 1 KHz	Typically 5 Hz to 20 KHz
Installation	Relatively Easy	Critical for High Frequency Measurements
Reliability	Relatively Short-Term; Performance Can Degrade; Rugged Under Normal Use	Good Long-Term (with proper care)
Environment	Good	Good for Higher Temperatures
Cost	Lower	Higher

accelerometer is superior to the velocity pickup for all applications.

But the previous section illustrates that this may not be true for the lower end of the frequency spectrum. It may be true only sometimes in the middle frequency region, where apparently both velocity and acceleration could be used. Actually, both are used in this frequency region, for various applications.

Although special construction techniques can extend the range of some velocity transducers to well above 1 KHz, an accelerometer is the usual choice for applications above 1 KHz.

In general, acceleration measurements emphasize higher frequency signal components. Displacement will emphasize the lower frequencies.

Installation and reliability

For a certain middle frequency range, perhaps 20 or 30 Hz to 1 KHz, none of the transducer characteristics discussed thus far has revealed an obvious choice. If both types have acceptable performance in this region, we must evaluate some other aspects.

Installation requirements and transducer reliability bring out advantages and disadvantages of both transducer types. Installation requirements would seem to be similar for both velocity and acceleration transducers. Both are usually mounted on a bearing housing. The attachment must be reasonably perpendicular and provide good flush contact with the mounting surface. However, if the accelerometer is intended to measure high frequencies, the method of attachment, in particular, becomes more critical.

Sometimes a bearing housing cannot be ground smooth enough for flat surface-to-surface contact for an accelerometer. In this case, an intermediate mounting block will be necessary (API 678 requires this). For most applications, a combination attachment works best. A stud (with proper torque) plus a thin film adhesive (epoxy) mounting will produce the desired high frequency response. In effect, this means that most accelerometer installations should be considered permanent. Usually, magnetic base and hand-held techniques provide little more frequency range than with a velocity transducer.

In general, the mounting requirements for velocity seismoprobes are less stringent than for accelerometers, although low frequency models have mounting restrictions as to orientation angle.

Reliability, on the other hand, seems to favor the accelerometer. Since the velocity transducer is a spring-mass-damper mechanical system, some degradation in performance under normal use can be expected over a period of time.

Most manufacturers recommend a calibration check annually for the velocity transducer, and warrant their specified performance for no more than two years. Warranties for accelerometers may not be any longer, but their record of long-term reliability in the field, *assuming no abuse*, is better.

On the other hand, a velocity transducer can take more abuse on a routine daily basis than an accelerometer. An accelerometer may be specified for high shock loads, but the rating usually is only for the sensitive measurement axis. A velocity transducer can usually withstand more abuse in the cross-axis direction.

Environmental factors

Both transducer types can be applied in similar industrial environments. This is especially true if the installation is good, i.e., a surrounding junction box (not contacting the transducer) providing environmental as well as mechanical protection.

Temperature may be the only deciding environmental factor. Here again, there is a compromise.

Accelerometers (with external change amplifiers) can be designed to meet higher temperature environments, but suffer more from thermal shock and ambient temperature gradients. A high temperature application generally means that the machine casing is extremely hot due to the internal gas or liquid, not necessarily the ambient machine environment.

Unacceptable signal noise may be produced by a significant temperature differential from the top of an accelerometer to its mounting surface. Also, thermal waves radiating from the hot mounting surface may cause additional noise.

Cost

Hardware cost is never an unimportant factor, but in this evaluation, it is not a very decisive one, either. In general, accelerometers, particularly the high frequency and high temperature models, are more costly than velocity transducers. But they also generally require less frequent replacement, at least from the standpoint of normal performance degradation. And in most systems, transducer costs are relatively low compared to the typical investment in monitoring and analysis instrumentation.

Signal conditioning

Some of the compromises made in the transducer selection process can be somewhat tempered by certain types of signal conditioning circuitry. The electronics can be in either an interface module or a monitor/readout instrument. Three signal conditioning techniques used often are signal integration, filtering, and amplitude/phase compensation. All are available in certain monitor systems and are usually incorporated in portable instruments used for vibration analysis.

Signal integration

An integration circuit is used to convert either a velocity signal to displacement or an acceleration signal to velocity. If, for a given application, a particular vibration engineering unit is desirable, but the transducer that measures directly in those units cannot be used (for whatever reason), then signal integration is a viable alternative.

Some users prefer accelerometers over velocity pickups as a fundamental housing measurement transducer, but place more value in velocity than acceleration engineering units as an overall indicator of machinery condition. In this case, the accelerometer signal would be integrated to velocity.

Integration also is used when it is desirable to measure housing vibration displacement. Since no commonly used transducers measure seismic (absolute) displacement, a velocity pickup is normally employed with its signal integrated to displacement. Double integration of an acceleration signal to displacement is also possible. But, because acceleration units emphasize the higher frequency components, very high gain is required to give value to the lower frequencies. Often times this gain amplifies the noise level as much as the real signal, producing a meaningless double-integrated signal.

Signal integration has definite value for machine analysis and monitoring purposes. As explained above, since displacement, velocity, and acceleration each measure different characteristics of the same vibratory motion, evaluating that motion

in two, or all three, of the units can be more informative than using only one.

The dual probe is a combination transducer system using a proximity probe for shaft relative vibration and a seismic transducer for bearing housing absolute vibration. In order to compare shaft relative and housing absolute motion, the housing measurement signal must be integrated to displacement. Also, to determine shaft absolute motion, the instantaneous time summation of the shaft relative and housing absolute *displacement* waveforms is required. If the seismic tranducer is a velocity seismoprobe, single integration is required; double integration is required if it is an accelerometer. In this application, a velocity sensor is preferred, since single integration is less noise susceptible and is a more reliable process than double integration of an acceleration signal.

Often, filtering of the acceleration signal prior to double integration is required to provide adequate signal quality. However, such additional circuitry adds an unnecessary degree of unreliability for monitoring applications. In addition, the difficulties of using the accelerometer in the low frequency region will limit the use of the complete dual probe assembly (for shaft absolute measurements).

Finally, in some applications, housing measurements are used for reasons of tradition, economy, and/or installation difficulty on machine types that technically would be best measured by shaft displacement transducers. For these situations, housing displacement measurements derived from integrated velocity signals may be the next best alternative.

Filtering

Sometimes optimum transducer performance and usefulness is limited because of erroneous signal noise or the capture of unwanted vibrations. If the useless information is contained within a particular frequency domain, then filters in the signal conditioning circuits may help.

For unwanted signal frequencies that lie entirely in a range above or below the range of interest, low-pass and high-pass filters can be used. When erroneous signals lie within the desired frequency range, the application of band reject (notch) or combination low-pass/ high-pass filters can be considered.

In all cases, the exact filter characteristics (bandwidth, Q, rate of roll-off, etc.) must be known before they are used. When filters are used correctly, they may improve signal-to-noise ratio and overcome some of the difficulties of signal integration. But when used without complete knowledge of the filter's performance and specific machine behavior, some meaningful information may be lost in the process.

Amplitude/phase compensation

For most velocity transducers, the specified lower frequency limit is that which the amplitude response is attenuated by a certain amount, e.g., minus 3 dB or 70.7% (down by 29.3%). At that point, there is also some phase (lag or lead) error. Below this point, although the transducer's response is even less accurate, the signal may still be weak if the exact response is known and repeatable. A signal conditioning circuit that is "matched" to the amplitude and phase response can be used to minimize these errors in this frequency region.

This circuitry can be incorporated in a monitor system or may be provided in portable readout instruments. It is essential for monitor systems on low speed machines, such as cooling tower fans. It is also useful for obtaining accurate data during start-up and shutdown, and for low speed balancing situations.

Conclusions

When choosing any monitoring system, portable or periodic, some basic questions must be answered in the following order:

1. What is the machine type and the design of its components, and what are the process conditions?
2. What are the most likely problems that could occur on this machine?
3. How will the machine's vibration characteristics change if each of the above problems occur?
4. What systems of transducers and signal conditioning circuitry will best measure the above vibration changes and meet the mechanical and environmental requirements of the installation?
5. Which system provides the best cost/ benefit ratio?

Equally important to consider are the basic objectives of the monitoring system. What level of information is expected from it? Who in the plant will need this information to make decisions about the machine? Is the system simply to protect the machine against very severe damage or is it to provide diagnostic level information to the plant's rotating machinery specialist?

Any one of several systems might be adequate for providing some warning prior to total machine failure. But the selection process must be more careful for a system intended to detect machine problems early in their occurrence and provide insight into the nature of the problem as well.

The characteristics of velocity and acceleration transducers are summarized in Table III. For certain applications of housing measurement transducers, there is a clear choice. The velocity transducer is generally more useful for very low frequencies and the accelerometer alone is applicable for very high frequencies. In the middle frequency domain, either type might be used with success for particular applications. Since the consideration of all other factors does not reveal an obvious superiority of one over the other for some applications, choice becomes as much one of personal preference and/or specific application as anything else.

We welcome your comments on this subject. We would like to know if you agree with our observations, or if in your experience, you have gained some knowledge which provides a more decisive choice between velocity and acceleration transducers for general or specific applications. Please write Mark Gilstrap in Minden.

For more information, check the following L numbers on the return card:

Acceleration Transducer System, L0041.

Low Frequency Seismoprobe Velocity Transducer, L0156.

Velocity Transducer System, L0393.

General Purpose Velocity Transducer, L0456.

Machine Protection System for Various Types of Rotating Equipment, Part Two, L0235.

June 1983 Orbit, L8009.

March 1983 Orbit, L8008. ■